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PLEISTOCENE-HOLOCENE PERMAFROST OF THE EAST SIBERIAN EURASIAN ARCTIC SHELF

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Abstract

Cryolithosphere dynamics in the East Siberian Eurasian Arctic shelf during the last 50,000 years were reconstructed on the basis of paleogeographic events including transgressions and regressions of the Arctic Ocean, and changes of paleoclimatic environmental conditions within subaerially exposed shelf areas after their flooding by sea water. Mathematical models and calculations were developed in accordance with these events. Three transgressive and three regressive stages in the evolution of the Arctic shelf were established for the last 50,000 years. Air and permafrost temperatures and their spatial and temporal variations were reconstructed for regressive epochs, while sea bottom temperatures, salinity and "overburden pressure" were reconstructed for transgressive periods. The possible thickness of permafrost in coastal areas is 345-455 m. The possible thickness of ice-bonded permafrost and non ice-bonded saline permafrost ranges from 240-350 and 20-25 m respectively in the central shelf, to 140-175 and 10 m in the outer shelf.

Introduction

The formation of the modern subaquatic cryolithosphere (offshore permafrost) on the Eurasian Arctic shelf is usually assigned to the Pre-Holocene (Sartan) regression, and complete or partial degradation of the permafrost, to the subsequent (Flandrian) transgression. The nature and extent of permafrost paleoreconstructions for particular time periods differ considerably depending upon the extent of Sartan regression, sea level change, and paleoclimatic characteristics of the drained shelf area. Calculations of permafrost degradation during the subsequent transgressive epoch also vary considerably in accordance with the characteristics of the sea basins that are assumed.

Different authors have calculated the freezing depths of exposed shelves during the Sartan epoch. Permafrost may have reached 600 m on the Barents Sea (Bondarev et al., 1995), 300-500 m for the Laptev Sea (Zhigarev et al., 1982), and up to 550-775 m in coarse grained sediments and 1000-1100 m in solid rock (Fartyshev, 1993). These authors disagree on the estimates of permafrost degradation during the Holocene transgression. For instance, the map of the modern cryolithozone (permafrost) thickness in the Laptev Sea shelf displays values obtained at the time of the regression maximum (Fartyshev, 1993). However, other profiles reflecting cryolithozone evolution in the Laptev Sea (Zhigarev et al., 1982) show that permafrost which formed during the Sartan regression has completely or partially degraded, and now is either absent or represented by isolated islands.

Therefore, in order to solve this contradiction it is necessary to estimate the extent of the Sartan regression. In the eastern sector of the Eurasian Arctic shelf, the sea level fall is estimated variously at 110-120 m (Aksenov et al., 1987), 100 m (Fartyshev, 1993), 90-100 m (Hopkins, 1976), 50 m (Zhigarev et al., 1982), and (minimum) 30-50 m (Danilov and Zhigarev, 1977). The authors, estimating the sea level fall at 100 m or more, consider it to be glacioeustatic. However, in this case it is necessary to examine the location of the great ice sheets that sequestered so much oceanic water. During regressive epochs, glacial ice did not cover the East Siberian shelf and was far enough back on land. Hence, the influence of glacioeustatic effects and glacial sedimentation were not considered (Danilov, 1985, 1987).

Paleoreconstructions of the Shelf Evolution During the Last 50000 Years

Paleoreconstructions given below are mainly based on actual data from the East Siberian sector of the Arctic Seas. Reconstructions of sea level dynamics during the last 150,000 years are possible because paleoevents of the Sartan regression and the preceding Karga transgression yield reliable radiocarbon dates.

The Karga transgression formed a well-defined coastal terrace with absolute height ranging from 25 to 35 m (Danilov, 1978). Its age estimations vary from 50-45 to 25-24 ka (Danilov, 1987). The end of the Karga transgression marks the beginning of the Sartan regression which reached its maximum 18-20 ka.

There are two possible ways to solve the problem of the lowermost sea level position in the Arctic: to determine the position of the Lower Holocene alluvium base in the mouths of major rivers (i.e. to determine the depth of downcutting in the coastal zone), and to analyze flooded coastal landforms and continental deposits on the sea floor. It has been established that the depth of downcutting at the mouths of major Siberian rivers is 30-50 m (Danilov, 1978).

Flooded coastal landforms and terrace-like surfaces are well-defined on the Eastern Eurasian Arctic sea floor. In the Chukchi Sea, flooded coastlines and related river paleovalleys have been traced down to the depths of 41-52 m (Hopkins, 1976). Radiocarbon dates of coastal-deltaic sediments and marine clayey muds sampled in the Hope submarine valley indicate that depths of 52 m and greater were flooded prior to 16 ka, and depths of 41 m and greater were flooded prior to 14.6 ka (McManus and Creager, 1984). Deposits found at depths of 38 and 30 m yielded age estimations of 13.0 and 11.8 ka, respectively.

Flooded coastlines and accumulative submarine landforms of the Laptev and East Siberian Seas are the best preserved and studied. They are restricted to depth intervals of 50-55, 40-45, 30-35, 20-25, and 10-15 m. In the Laptev Sea (north-eastern region), the following radiocarbon dates were obtained within the depth range of 45-55 m: 18.4; 15.0 and 14.2 ka (Holmes and Creager, 1974). The authors consider the 14,200 date to be representative, while the other dates are thought to be erroneous due to incorporation of additional carbon. However, in such cases the age usually becomes younger rather than older. The authors are forced to consider the date 14.2 ka correct because this age and the depth 50-40 m correlate better with the universally accepted glacioeustatic curve (Holmes and Creager, 1974). According to this curve, the 18-20 ka sea level of the World Ocean was restricted to the depths of 100-120 m and more. Ignoring the glacioeustatic curve, the oldest date, i.e. 18.4 ka, should be considered as more relevant. It seems to be the most reliable record of the sea level history in the East Siberian sector of Arctic at depths of 40-50 m. A stand-still of sea level at the depths of 50-55 may be dated at 18-20 ka, and that at 40-45 m, at 16-18 ka. Submarine terraces at the depths of 30-35 and 20-25 m have not yielded any absolute ages. The youngest coastline at the depths of 10-15 m yields the date of 10.25 ka (Fartyshev, 1993).

In order to estimate the duration of the Sartan regression, it is necessary to date both the time of its termination and the time of shelf flooding. Various data on the coasts and bottom sediments of Siberian seas suggest that the Mid-Holocene sea level exceeded its present position. Bars and terraces with the heights of 2-3, 4-5,

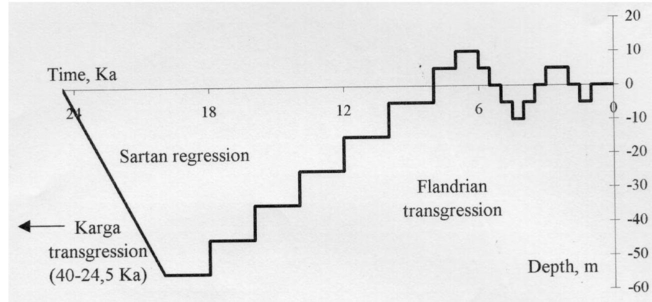

Fig. 1. Sea Level Oscillations in the East Siberian Sea During the Last 25 ka.

Table 1. Paleotemperature Data for the Last 25 ka Paleotemperatures for the regression periods are shown in the shaded cells

Age, Ka	Coastline position (abs. height), m	Distance of coastline from its present position, km	Average multi-annual temperature		
			Surfaces of the coastal zone, °C	Surfaces of the central shelf zone, °C	Surfaces of the outer shelf zone, °C
24.5	-5	50	-14.0	-1.50	-1.50
24.0	-15	150	-15.0	-1.55	-1.55
23.0	-25	250	-17.0	-19.5	-1.60
22.0	-35	350	-19.0	-21.5	-1.70
21.0	-45	450	-21.0	-23.5	-1.80
20.0	-55	550	-23.0	-25.5	-28.5
19.0			-25.0	-27.5	-30.5
18.0	-45	450	-24.0	-26.5	
17.0			-23.0	25.5	-1.9
16.0	-35	350	-22.0	-24.5	
15.0			-21.0	23.5	-1.80
14.0	-25	250	-20.0	-22.5	
13.0			-19.0	21.5	-1.70
12.0	-15	150	-18.0	-1.70	
11.0			-17.0	-1.60	-1.60
10.0	-5	50	-16.0	-1.50	-1.50
9.0			-15.0	-1.55	-1.55
8.0	+5	-50	-1.50	-1.50	-1.50
7.0	+10	-100	-1.45	-1.45	-1.45
6.0	0	0	-1.40	-1.40	-1.40
5.5	+5	-50	-13.0	-1.45	-1.45
5.0	-5	50	-14.0	-1.50	-1.50
4.5	-10	100	-15.0	-1.55	-1.55
4.0	-5	50	-16.0	-1.60	-1.60
3.5	0	0	-15.5	-1.55	-1.55
3.0	+5	-50	-1.55	-1.55	-1.55
2.0	0	0	-14.0	-1.50	-1.50
1.5	-5	50	-1.45	-1.45	-1.45
1.0	0	0	-13.0		
0.0			-14.0	-1.50	-1.50

and 10-12 m have been reported on the Chukotka coast (Danilov et al., 1980), and those with the heights of 2-3, 5-7, and 10-11 m on the coasts of the Laptev and East Siberian Seas (Fartyshev, 1993). The Flandrian transgression maximum is usually dated at 7-5 ka, and the sea level reached its modern position about 8 ka. The data indicate that the duration of the Sartan regression was about 17 ka (i.e. 25 ka to 8 ka). Short (1-3 kyr) sea level oscillations occurred during the last 8000 years. Their vertical amplitude did not exceed 10-20 m.

Parameters of the Numerical Model

The above paleoreconstructions served as the base for creating a model showing evolution of the shelf and the cryolithosphere within the East Siberian sector of the Eurasian Arctic during the last 50,000 years. Paleotemperatures, age estimations, and sea-level heights are shown in Table 1.

The coastline has experienced the following changes (Figure 1). Stabilization of the Sartan regression (20-18 ka) occurred at 55 m. Then the sea level experienced a fluctuating rise up to 45, 35, 25, 15, and 5 m with assumed stabilization for 2000 years at every mark. The surfaces of coastline stabilization formed during the Holocene transgression were used for establishing a series of steps for making the calculations (Figure 2).

In order to determine the extent of freezing during the Sartan regression, we assumed that by its start, the temperature of the bottom sediments corresponded to the temperature of the bottom water layer. Also, several additional assumptions were made. These are: the dynamics of temperature profiles and fronts of freezing-thawing are considered in a one-dimensional approximation; water and salt migration and mechanical deformations are ignored; and the thermophysical characteristics of the sediments are constant in blocks.

The calculation was made for each step using two layers with a combined thickness of 1000 m (45 m for the upper layer and 955 m for the lower). We used a specific scenario of time dependent temperature variations in order to set the limiting values for the upper boundary: at the beginning of modelling the average multi-annual surface temperature was set at -1.5°C with designated temperature distribution with depth, gradient 0.025-0.035°C/m. For regressive epochs it was the average multi-annual surface temperature, while for transgressive ones the bottom water temperature was used. The influence of radiant heat exchange was indirectly considered for coastal zone (Zhigarev et al., 1982). The terrestrial heat flow was set at 0.041 W/m^2 at the lower boundary (Fartyshev, 1993; Geotermicheskaya Karta SSSR, 1970).

Thermophysical properties, temperature of phase transitions, and water contents were taken from various publications (Komarov et al., 1987; Motenko and Komarov, 1996; Teplofizicheskie Svoistva.., 1984) and used to describe a two-layered lithological sequence. Geological and thermophysical parameters are given in Table 2. In accordance with salinity values (by averaging in the required range), unfrozen water content was set at 4.5-13% in the upper part of the section. Salinity was not taken into account for the lower part of the section.

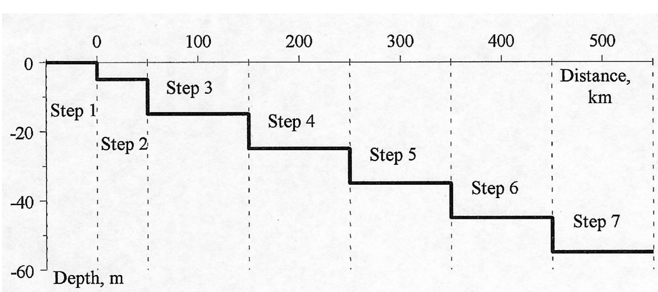

Fig. 2. Schematic Profile of Coast and Shelf, the East Siberian Sea.

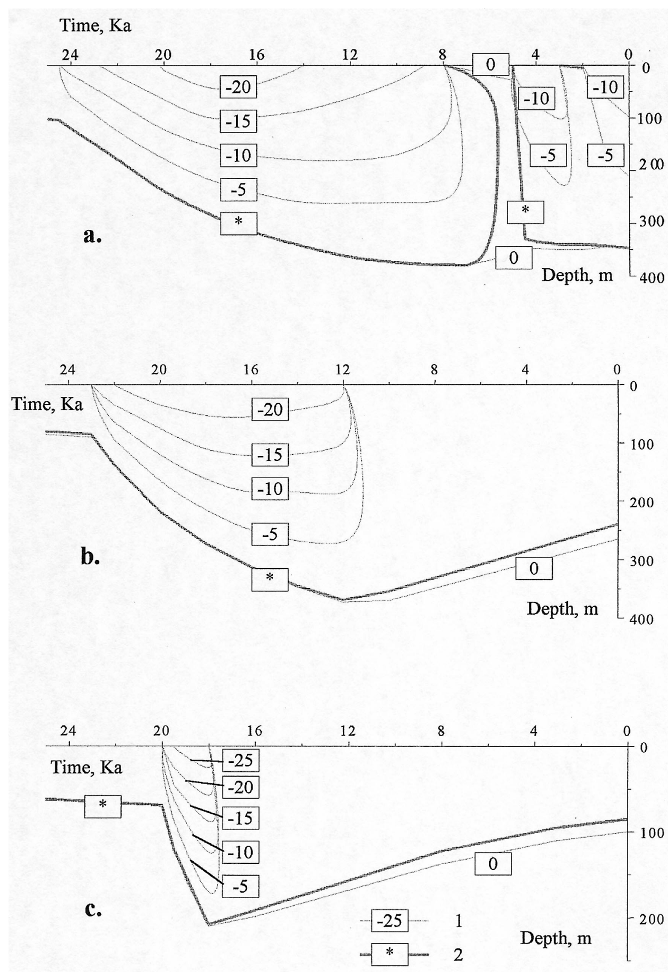

Fig. 3. Dynamics of Temperature Fields and Freezing-Thawing Fronts in the Permafrost Body at Different Terrestrial Heat Flow Values: a) coastal area; b) central shelf; c) outer shelf.
1 - isotherms; 2 - freezing-thawing front.

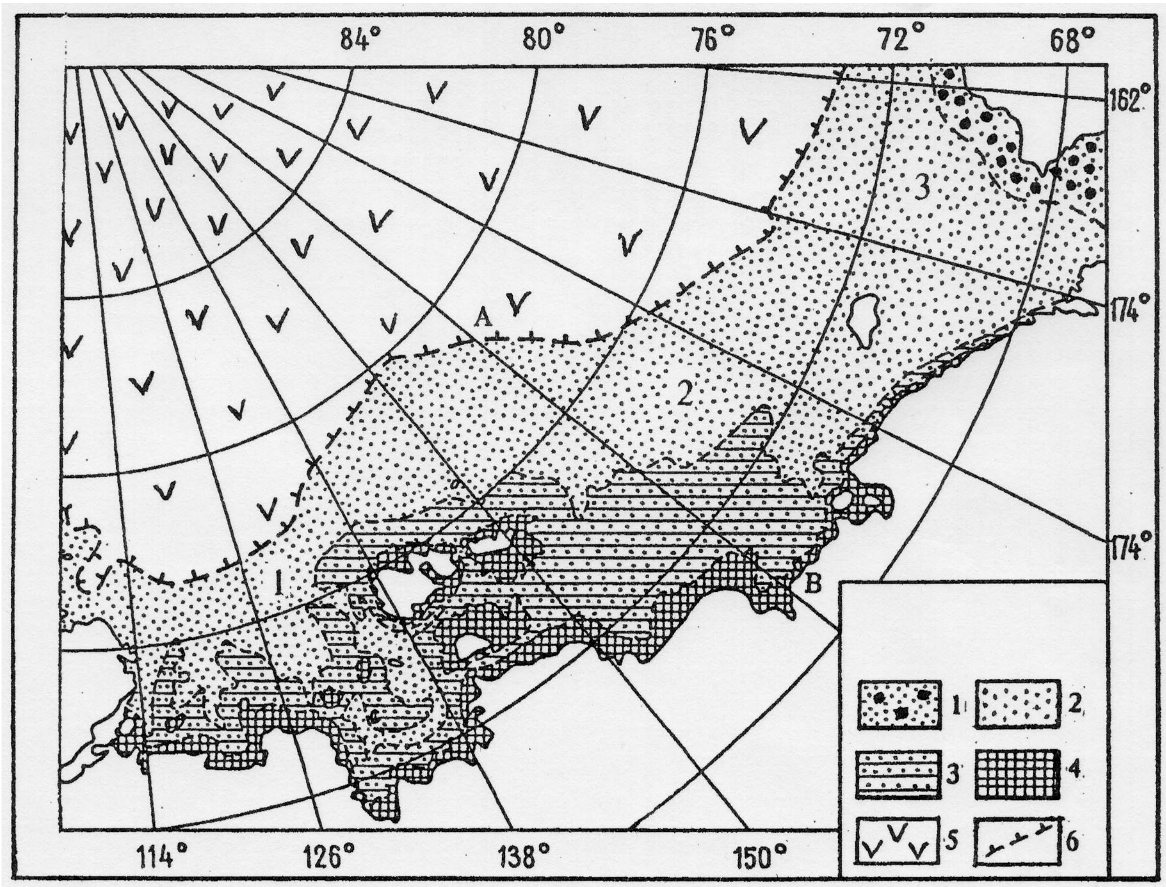

Fig. 4. Model Predictions of Submarine Permafrost in the East-Siberian Sector of the Arctic Shelf - the Laptev (1), East Siberian (2), and Chukchi (3) Seas. Key: 1 - permafrost absent; 2 - scattered Upper Pleistocene ice-bonded permafrost (up to 100 m thick) and Upper Pleistocene and Holocene non ice-bonded saline permafrost; 3-4 – continuous ice-bonded Upper Pleistocene permafrost (3 - with thickness up to 250 m, 4 - with thickness up to 350 m) overlain by Holocene non ice-bonded saline permafrost; 5 - oceanic cryolithozone beyond the shelf area (non ice-bonded saline permafrost); 6 - the outer shelf margin. (The boundaries of cryogenic areas follow those of V.A. Solov'ev (1983) with several alterations).
A-B - position of calculated profile (along 162°E).

Results of Mathematical Modelling

In order to calculate the permafrost thickness we used the program worked out in the geocryological chair of the Moscow State University (Khrustalev et al., 1994). The following results have been obtained.

COASTAL ZONE

During the Sartan regression, this zone was exposed from 24.5 ka to 8.0 ka. Three hundred and eighty meters of permafrost was formed during this period (Figure 3a). About 8.0 ka, the sea level exceeded its modern position (the Flandrian transgression), thus causing the permafrost temperature to rise. Heat exchange through the upper permafrost surface together with terrestrial heat flow from below resulted in partial degradation and its transition to non ice-bonded permafrost (cryotic or saline sediments with negative temperatures containing liquid water). The upper and lower boundaries of the non ice-bonded permafrost layer were situated at 50 m and 350 m respectively. Further draining, which began during the second half of Holocene (5 ka), resulted in several changes, i.e. thawed and cooled sediments became frozen again. Permafrost temperatures dropped, and aggradation of the permafrost started. Since the Holocene transgression was short, further degradation of permafrost did not occur, and, according to our calculations, its present thickness is 370 m.

Table 2. Sediments geology and physical parameters

Layer		Upper	Lower
Age		Quaternary	Cretaceous-Paleogene
Lithology		silts, loamy sands, and loams	dense clays
Thickness, m		45	955
Water content, %		25	15
Density, kg/m^3		1800	2000
Thermal conductivity of sediments, W/m·^{0}C	in frozen state	1.45	1.75
	in thawed state	1.3	1.6
Heat capacity of sediments, kJ/m^3·^{0}C	in frozen state	130	108
	in thawed state	131	128
Latent heat, kCal/M^3		36000	24000
Freezing (thawing) temperature, ^{0}C		-1.2	-0.1

CENTRAL SHELF ZONE

The central shelf zone was exposed from 23.5 to 12 ka. Three hundred and fifty meters of permafrost was formed during this time span (Figure 3b). The Flandrian transgression caused the permafrost temperature to rise and the permafrost partly degraded. By now its thickness is 220 m. It is underlain by a layer of non ice-bonded saline permafrost with a thickness of 20 m.

OUTER SHELF ZONE

The outer shelf zone remained exposed from 20 ka to 18 ka, during which time a 200-m thick permafrost layer was formed (Figure 3c). Subsequent flooding resulted in the permafrost temperature rise and partial degradation of permafrost. Calculations reveal its present thickness to be about 90 m. A 10-m thick layer of non ice-bonded saline permafrost has been formed below it. The results of the modelling are displayed in Figure 4.

Conclusions

The main implication of the performed modelling is that ice-bonded and non ice-bonded permafrost should exist within the shelf of the East Siberian sector of the Eurasian Arctic. The possible thickness of ice-bonded permafrost sediments in coastal area is 345-455 m. In the central shelf area (isobath 25 m), the possible thicknesses of ice-bonded and non ice-bonded saline permafrost are 240-350 and 20-25 m respectively. At the outer shelf margin (isobath 55 m) they are 140-175 and 10 m thick respectively.

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